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Preliminary Long-Period Discrimination Results from NORSAR

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Lexington, Massachusetts

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LINCOLN LABORATORY

PRELIMINARY LONG-PERIOD DISCRIMINATION RESULTS FROM NORSAR

R. W. WARD

Group 64

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ABSTRACT

Data from the short-period vertical subarray near Oyer and the multicomponent long-period seismograph near Faldalen, Oyer and Trysil, Norway, were used to investigate the discrimination of earthquakes and underground nuclear detonations using long-period to short-period energy ratio (M_s vs m_b).

Accepted for the Air Force
Franklin C. Hudson
Chief, Lincoln Laboratory Office

INTRODUCTION

Data from the short-period vertical subarray near Oyer and the multicomponent long-period seismographs near Faldalen, Oyer and Trysil, Norway, were used to investigate the discrimination of earthquakes and underground nuclear detonations using long-period to short-period energy ratio (M_s vs m_b). These stations were installed as part of the site survey for the Norwegian Seismic Array (NORSAR).

To insure first that the long-period instruments were operating normally and that the data is comparable with that recorded elsewhere, the surface wave magnitude (M_s) recorded at LASA and Faldalen was studied for a population of 21 events, and then a further comparison was made between the three Norway sites using a population recorded at at least two of them.

The M_s vs m_b relation for four populations of events recorded at LASA was compared with initial data from Norway. The surface wave magnitude[1] was computed from the amplitude of the 20-second period Rayleigh wave using

$$M_s = \log A - \log B$$

where A is the zero-to-peak amplitude of the 20-second Rayleigh wave, in millimicrons, recorded on a long-period vertical instrument and log B is determined from epicentral distance by

$$\log B = 1.182 - 1.656 \log (\Delta)$$

where Δ is the epicentral distance in degrees.

The body-wave magnitude (m_b) was determined from the amplitude of the short-period vertical wave recorded at teleseismic distances,[2] using

$$m_b = \log W/T + Q + S$$

where W is the maximum zero-to-peak amplitude (in millimicrons) of the first four cycles of the P-wave, T is the period (in seconds) of the short-period cycle used, Q depends on epicentral distance and is tabulated in Fig. 5 of a paper by Gutenberg and Richter,[2] and S is a station correction which is taken to be zero for convenience.

With the commencement of data acquisition in Norway we had an opportunity to investigate the western United States region at teleseismic distances. This permitted a study of the character of M_s vs m_b, as well as its effectiveness as a discriminant, for events from this region. The data obtained provides grounds for some speculation on the peculiarities of the western United States.

The M_s and m_b values were computed on the data analysis console.[3] This approach offered precise determination of M_s and m_b while permitting maximum human interaction when analyzing the data, e.g. bad channels could be detected, and time delays for beams could be theoretically determined or hand picked.

INTER-SITE COMPARISON OF SURFACE WAVE MAGNITUDE

Twenty-one events were found with surface waves observed at both Faldalen and LASA. Figure 1 shows the M_s at NORSAR vs the M_s at LASA, for the events listed in Appendix I, as determined from the LP vertical component of the Rayleigh wave. The scatter about the 45^o line in Fig. 1 must be attributed to source-medium difference between the sites, observational error, local effects and instrumental difference. These differences must account for an M_s at LASA 0.6 higher than Faldalen, to 1.1 lower than Faldalen. Since we are not able to remove the marked variation between the individual events, we will adopt the viewpoint that each of these factors contributes to one of two types of differences. One averages out over a large sample of events; the other introduces a bias when an average is taken. However, the populations of events which we use are not large enough for effects with zero mean to completely average out.

Earthquakes in general have a lobate radiation pattern. The observed magnitude of an event will be azimuthally dependent unless a correction is made. Since the source type and fault plane dip and strike are not known for these events, we can make no correction for the source difference. However, when the differences in radiation pattern seen at two sites are averaged over a large number of events, the effect tends to cancel out. We idealize this source difference as having zero mean.

The travel path from the epicenter of each event to Faldalen or LASA may be quite different. Surface waves can be scattered by continental margins, mountains, and other large scale changes in the crust and upper mantle structure. The most pronounced medium effect on surface waves at Norway occurs on events from Asia. Figure 2 displays a striking example of the medium effect on a Rayleigh wave seen at Faldalen from

the Hindu Kush region. Following the 20-second Rayleigh wave marked by the cursors a large apparent Airy phase arrives. This represents energy in a dispersive wave train which has not been dispersed. Both continental and oceanic crust-upper mantle models have Airy phases. However, a given travel path crosses varying crustal structures. Hence the period at which an Airy phase propagates in one region is dispersed by the next. The presence of Airy phases from Asian events indicates that the travel path from these events encounters very nearly identical crust-upper mantle structure along its path to Faldalen. Regions with events exhibiting Airy phases at Faldalen are E. China Sea, Kurile Islands and Hindu Kush. The group velocity curve of Rayleigh waves for an average continental structure is nearly flat at 20-second period indicating that Airy phases occur at this period. The group velocity curve for an average oceanic structure is quite steep, indicating significant dispersion of 20-second period energy. Asian events have purely continental paths to NORSAR but mixed oceanic-continental paths to LASA. Since a large number of Asian events are included in our sample, we expect the travel path effect to give an average bias of larger M_s values at NORSAR relative to LASA.

The local effects are of two types: differences in local surface wave velocity, and local scattering and noise. Though a surface wave at two sites may have the same energy, the amplitude will be smaller at the site with the higher Rayleigh wave velocity. The local scattering of events and interference is more difficult to evaluate. One expects this to be azimuthally dependent. The local effects could introduce a bias into the average difference in M_s between two sites.

The observational error we assume has zero mean. Any instrumental differences would, of course, bias the data. Therefore, any mean difference between LASA and

Faldalen must be explained by the effect of differences in the travel path to each site, local effects or instrument bias. The mean difference in M_s [M_s (Faldalen) – M_s(LASA)] for the events in Fig. 1 is 0.3. The solid line in Fig. 1 is shifted by this mean difference above the 45° line. Far more travel paths to Norway than to LASA cross purely continental structures. Since the purely continental path scatters and disperses less surface wave energy, we expect the average effect of travel path differences will give larger M_s values at Faldalen. For this reason we take the mean difference as an approximate upper bound on the instrumental difference and the local effects.

To further assess the extent of local effects and compare M_s values measured at the three LP sites in Norway we computed the mean difference in M_s for those 13 western U. S. and Mexican events (Appendix II) which were observed at more than one of the three Norway LP sites (Faldalen, Trysil and Oyer). Since these events have nearly the same travel path, only instrument bias or local effects will plan an important role. The mean difference for individual sites was:

Oyer – Faldalen	Oyer – Trysil	Faldalen – Trysil
0.1	– 0.3	– 0.3

[Note that (O – F) + (F – T) $\neq$ (O – T), since all sites did not record each event.]

We find differences between individual sites in Norway as great as the differences between Faldalen and LASA. These differences are not considered unusual and are probably due to azimuthally dependent local effects and differences in local crustal structure, not instrumental differences. An approximate upper bound for a mean difference appears to be 0.3 for individual sites. One must be aware, however, that the M_s difference between two sites varies erratically from event to event. For the small populations

of events used in this study, the effects we assume to have zero mean will not average out. The numerical values determined for intersite mean differences are only approximate. Use of beamforming techniques using the entire projected LP array ought to partially average out these local directional differences in sensitivity and local crustal structure differences.

THE M_s VERSUS m_b DISCRIMINANT

The relationship of M_s vs m_b as determined from data recorded at LASA has been examined for four regions of the world[4] by Capon, et al. Since this discriminant has been successfully applied at LASA, we want to compare its relative effectiveness for data recorded at Norway. Figure 3 shows the LASA M_s vs m_b relationship for the four regions determined by Capon, et al. Figure 4 presents the M_s vs m_b determination at Norway for 26 events of various depths occurring outside the western U. S. and Mexico. Unfortunately, this population contains only one presumed explosion and only an upper bound on its surface wave magnitude was obtained. These events are listed in Appendix III.

The M_s vs m_b values of events from N. E. China, Hindu Kush and Turkey lie near the explosion region in Fig. 4. Figure 5 presents events with $M_s \geqq 3.0$ and depth less than 50 km as determined by the U. S. Coast and Geodetic Survey. These events are listed as "shallow events" in Appendix III.

The exclusion of deep events and undetermined depth events from the M_s vs m_b plot gives a significant improvement in the separation of the earthquakes and the one explosion. Yet for this preliminary data no definite conclusions concerning the effectiveness of the discriminant M_s vs m_b at Norway can be drawn.

WESTERN UNITED STATES EVENTS

According to Liebermann and Pomeroy,[5] the $M_s - m_b$ values determined for western U. S. events are anomalous compared with the world average for both explosions and earthquakes. The data supporting this hypothesis were recorded within continental North America at World Wide Standardized Seismic Stations (WWSSS) and Long Range Seismic Measurements (LRSM) stations. Their separation from six earthquakes and five Nevada Test Site (NTS) underground explosions was complete. The earthquakes occurred in southern California, Nevada, Montana and New Mexico.

To confirm that similar results occur for measurements at teleseismic distances outside the continental boundaries of the epicentral region we have analyzed eight U. S. earthquakes, three Mexican earthquakes, four NTS explosions and one collapse of an explosion for M_s vs m_b. The m_b value was computed using the Oyer subarray and the M_s value from a long-period beam of Oyer, Trysil and Faldalen. Figure 6 presents the M_s vs m_b plot. The separation can be seen to be complete for this set of data. The $M_s - m_b$ values for the explosions fall within the world wide range of earthquakes and the earthquakes of the western U. S. appear to have either an M_s value above the world average or a low m_b value. The dashed line would separate earthquakes and explosions for the data of Fig. 3 determined at LASA. This anomalous behavior of the $M_s - m_b$ value for western U. S. events clearly confirms indications from Fig. 3 that earthquakes and explosions must be treated on a regional basis. The M_s vs m_b discriminant appears to discriminate completely for shallow events ($m_b > 5$) which have been regionalized.

CAUSE OF REGIONAL VARIATIONS IN THE M_s vs m_b DISCRIMINANT

The necessity that the M_s vs m_b discriminant be applied to regionalized populations of events could severely limit its use as a discriminant. Since most of the earth is aseismic, one will not always have a reference population of earthquakes from a given region with which to compare future events. Clearly, if an event from such a region has an M_s vs m_b value similar to that of an underground explosion from the western U. S., it could be classified as an explosion using the western U. S. population or as an earthquake using the Central Asia population. The problem of predicting a priori whether a given region is similar to the western U. S. or Central Asia is therefore of immediate concern. We try to correlate the M_s vs m_b characteristics of a region with the tectonic character and the upper mantle structure.

The cause of the upward shift of the M_s vs m_b values for events from the western U. S. relative to Central Asia can be examined from two viewpoints. Either the m_b value from this region is anomalously low or the M_s value is anomalously high. Of course both effects could be acting. We will now examine causes that can realistically account for these shifts.

We can account for the relative attenuation of body wave originating in one region relative to another by a relative difference in the Q of the low velocity layer. To establish an upper bound on the effect we consider a low velocity, low Q region with 300 km thickness. In Table I we list the attenuation experienced by waves of three frequencies for different Q. The Q effect can easily account for the shift in the M_s vs m_b plot, since at 1 Hz a change from a Q of 200 to 50 in this layer shifts m_b downward by 1.5. Such differences in Q may very well exist in the earth.

		Q			
		50	100	200	500
Frequency	0.5	$.9 \times 10^{-1}$	.3	.6	.8
	1.0	$.9 \times 10^{-2}$	$.9 \times 10^{-1}$	.3	.6
	2.0	$.8 \times 10^{-3}$	$.9 \times 10^{-2}$	$.9 \times 10^{-1}$	.4

TABLE I. Attenuation of a 300 km-thick layer
(Transmitted amplitude/incident amplitude)

As a preliminary estimate of the relative effect of Q, a mean spectrum for four populations of events recorded at NORSAR was determined. The populations consisted of U. S. explosions, USSR presumed explosions, western U. S. earthquakes and worldwide (excluding the U. S.) earthquakes. The spectrum of each event is the product of the source spectrum, the response of the source region, and the response of the receiver region. The response of the receiver is the same for all events, while the regional difference in source region response varies between the populations. By averaging we hope to obtain an average source spectra for the earthquakes and for the presumed explosions, though this may not be possible. Figure 7 shows the average spectrum for each population. The higher frequency components are attenuated more severely on the U. S. spectra than the others. This attenuation would occur if there is a regional Q difference. However, the effect we are observing may not be due to a difference in Q, but rather regional differences in source spectra.

The relative enhancement of the surface waves in one region relative to another is attributed to a different effect. Theory predicts that an explosive source in an infinite homogeneous medium will not generate SH waves. Yet it is well known that

nuclear explosions detonated at the Nevada Test Site (NTS) often generate very large Love waves. For a number of nuclear explosions Toksöz[6] has fitted a theoretical model to the observed data using amplitude equalization of the surface waves. By superposing an explosive source and a double couple source one can fit the observed ratio $|L| / |R|$ as a function of azimuth, (where $|L|$ is the maximum amplitude of the Love wave and $|R|$ is the maximum amplitude of the Rayleigh wave). One can then determine the source parameters such as fault plane orientation and dip, and the part of the source due to double couple relative to the explosive component. Toksöz finds the double couple component contributing as much as three times the explosive component. Similar calculations have been carried out by the author for later NTS shots, which also require significant double couple contributions. The source mechanism of an underground nuclear explosion near NTS must allow for a significant earthquake component as well as an explosive component.

The source of the SH wave generation has been investigated in environments where source conditions can be determined more precisely. Kisslinger et al[7] made measurements near the source of chemical explosions. SH waves were generated. When surface cracking occurred, it had a preferred orientation, which can account for the asymmetrical SH radiation pattern. Later model experiments reported by Kim and Kisslinger[8] give more conclusive results. Two-dimensional prestressed models were excited by an explosive source; shear waves were generated in the prestressed models but absent in the relaxed ones. Their work suggests "that the dominant role for S wave generation is attributable to the strain energy release rather than to directional cracking." The S wave generation is increased by increasing the ambient stress field and prefracturing around the shot hole.

If one assumes the models behave as the material of the crust, the generation of anomalously high surface waves by underground explosions can be attributed to anomalously high ambient stress fields in the upper crust. A recent article[9] synthesizes data from many areas into a global tectonic picture. The model distinguishes three layered regions of the crust and mantle. The uppermost mobile region, the lithosphere, has considerable strength on a geologic time scale. The lithosphere includes generally the crust and upper mantle to a depth of 100 km. Below the lithosphere is a rather weak region, the asthenosphere, extending to several hundred kilometers depths. The rest of the mantle is the mesosphere. This picture includes a continuation of an oceanic ridge from the Gulf of California along the San Andreas Fault to the west coast of Oregon and Washington. The depth of seismic activity along the San Andreas does not exceed 20 km and is only slightly deeper as one moves away from it. Near the ridge the lithosphere must possess a large ambient stress field in the upper most 20 km of the crust, sufficient to push apart the much thicker plates. An explosion detonated near the ridge of this lithospheric block will release substantial strain energy.

Earthquakes occurring in the western U. S. must also release more strain energy since their M_s vs m_b plot separates from that of the explosions in the region. To examine the M_s vs m_b character of earthquakes occurring near an oceanic ridge, the M_s vs m_b was determined for a population of 39 earthquakes near the mid-Atlantic Ridge. Figure 8 shows this plot. All but two of the events lie above the Gutenberg-Richter line, which is a linear fit to the worldwide average M_s vs m_b for earthquakes. These results support the belief that the M_s vs m_b character of oceanic ridges is anomalously high.

We have attributed the anomalous M_s vs m_b behavior of the western U. S. to two possible effects. Further investigation is necessary to determine which effect is actually contributing the most to the shift in the M_s vs m_b curve.

To determine the relative Q effect of the western U. S. with other regions of the world, one can compare the spectra of a deep impulsive event recorded at many stations. The event should have a focal depth of 600 km to insure that the first arrival traverses only the low Q region at the various receivers. By taking records from both the western U. S. and other areas one could evaluate the relative attenuation of the high frequencies. Equivalently one has a measure of the relative Q effect between regions.

The relative release of strain energy from region to region can best be studied after determining the Q effect. The M_s vs m_b relationship must be examined for a large number of events from different regions. The mean focal depth for these regions should be determined to study the ambient stress distribution. High near-surface ambient stress field should correlate well with high M_s vs m_b values for events from such regions. Large stress fields at depth will give smaller surface waves due to the lower excitation of surface waves by deep sources. If the release of strain energy proves to be the cause of higher M_s vs m_b values for nuclear explosions in the western U. S., one will be able to predict a priori the characteristic M_s vs m_b values for a region from a global tectonic model. Furthermore, one will have the assurance that aseismic regions will not produce anomalously high surface waves since they do not possess large ambient stress fields.

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Date	Region	O. T.	Latitude	Longitude	Depth	M_S LASA	M_S Faldalen
1/6/68	Bay of Bengal	15:13:28.7	16.4 N	92.1 E	33 R	4.0	4.3
1/7/68	N. W. Kuriles	13:50:42.0	49.1 N	151.3 E	284	3.1	3.7
1/8/68	N. Chile	18:44:24.5	18.6 S	69.9 W	116	4.3	4.6
1/8/68	Center mid-Atlantic Ridge	20:22:15.6	8.2 N	38.2 W	33 R	4.7	4.7
1/11/68	Mindano	01:12:12.3	6.9 N	126.1 E	160	5.0	3.7
1/12/68	Kermadec	03:05:18.5	27.2 S	177.2 W	90	4.0	4.2
1/12/68	Andaman Islands	04:17:43.1	13.4 N	93.1 E	33 R	3.3	4.0
1/19/68	Solomon Islands	06:04:38.2	9.4 S	158.4 E	33 R	5.7	6.5
1/19/68	Kurile Islands	16:05:02	45.0 E	147.0 E	---	3.3	4.0
1/20/68	Coast of Mexico	21:41:09.8	16.1 N	105.4 W	51	4.4	4.8
1/26/68	Kirghiz	09:22:57	41.0 N	75.0 E	---	3.5	< 3.4
1/26/68	Gulf of California	12:30:46.3	24.3 N	111.5 W	33 R	4.0	5.1
1/27/68	North Atlantic Ridge	01:41:35.4	30.0 N	42.8 W	33 R	4.6	4.0
1/16/68	Sicily	16:42:44.3	37.9 N	13.1 E	14	5.2	5.0
1/25/68	Tyrrhenian Sea	14:35:32.6	37.8 N	12.9 E	33 R	4.0	3.9
1/27/68	North Atlantic Ridge	00:48:33.6	29.9 N	42.8 W	34	4.0	4.5
1/27/68	E. China Sea	13:56:23.8	23.2 N	121.6 E	53	5.1	5.7
1/29/68	Afghanistan-U. S. S. R.	05:00:10.0	36.3 N	70.4 E	225	4.3	4.2
1/29/68	Kurile Islands	16:42:50.4	43.5 N	147.2 E	36	5.6	5.7
1/29/68	Gulf of Alaska	20:52:21.3	56.4 N	153.6 W	6	5.0	5.0
1/30/68	Kurile Islands	02:38:12.6	43.3 N	147.7 E	33 R	4.6	5.2
2/3/68	Kurile Islands	03:26:16.6	46.6 N	152.6 E	45	5.2	4.6

APPENDIX I

EVENTS USED IN COMPARISON OF M_s AT LASA WITH M_s AT FALDALEN

Date	O. T.	Region	Latitude	Longitude	Depth	M_s (Beam)	m_b (Beam)	M_s Oyer	M_s Trysil	M_s Faldalen
U.S. Explosions			approx.	approx.						
1/19/68	18:14:58	NTS	39.0 N	116.0 W	0.0	4.7	6.0	4.8	4.7	4.3
2/21/68	~15:30:00	NTS	39.0 N	116.0 W	0.0	3.9	5.4	n	4.0	n
3/22/68	~15:00:00	NTS	39.0 N	116.0 W	0.0	3.8	5.6	---	3.8	3.7
4/26/68	~15:00:00	NTS	39.0 N	116.0 W	0.0	5.1	6.0	5.2	5.0	5.0
5/17/68	13:00:00	NTS	39.0 N	116.0 W	0.0	i	4.5	i	i	i
5/17/68	14:11:25	NTS (collapse)	39.0 N	116.0 W	0.0	3.5	4.1	3.8	3.9	3.8
U. S. Earthquakes										
2/6/68	00:41:37.2	Calif-Nev Border	38.0 N	118.4 W	17	4.0	4.6	4.0	4.0	---
4/9/68	02:30:11	Southern California	34.0 N	116.1 W	20	> 6.2	5.3	---	> 6.2	---
5/8/68	21:53:03	Off Coast Oregon	43.9 N	128.2 W	33 R	4.7	4.9	3.8	5.2	4.2
5/8/68	22:17:14	Off Coast Oregon	43.9 N	128.2 W	33 R	4.5	4.5	3.9	5.0	4.0
5/30/68	00:36:00	Oregon	42.3 N	119.8 W	---	3.6	4.7	---	3.6	---
6/3/68	16:48:56	Off Cst. N. California	40.3 N	127.1	15	3.6	4.3	3.5	3.6	3.6
6/4/68	02:34:15	Oregon	42.3 N	119.9 W	21	3.6	4.7	3.7	3.7	3.7
Mexican Earthquakes										
1/26/68	12:30:46	Baja, California	24.3 N	111.5 W	33 R	5.2	5.2	5.2	---	5.1
6/9/68	10:21:36	Nr. C. Chiapas, M.	14.6 N	92.0 W	60	4.7	4.7	4.8	---	4.8
6/17/68	07:56:56	Nr. C. Chiapas, M.	14.4 N	92.9 W	33 R	4.5	4.8	4.6	---	4.3

--- Out

n No Measurement Made

i Interfering Event

APPENDIX II

WESTERN U. S. AND MEXICAN EVENTS

Latitude	Longitude	Depth	Region	M_s	m_b
Shallow Events					
16.4 N	92.1 E	33	Bay of Bengal	4.3	4.5
49.8 N	78.0 E	0	E. Kazakh	< 3.2	5.5
37.6 N	114.9 E	33	N. E. China	3.8	5.7
8.2 N	38.2 W	33	Atlantic Ridge	4.7	5.7
35.5 N	22.5 E	44	South of Crete	< 3.3	4.5
46.4 N	153.3 E	50	Kurile Islands	4.0	4.9
33.6 N	132.2 E	19	Shikoku	3.7	5.0
13.4 N	93.1 E	33	Andaman Islands	4.0	5.3
9.4 S	158.4 E	33	Solomon Islands	6.5	5.3
42.6 S	75.2 W	22	Chile-Argentina Border	5.0	5.3
29.9 N	42.8 W	34	North Atlantic Ridge	4.0	4.8
36.8 N	5.6 E	20	Tunisia	3.9	4.4
Deep Events					
49.1 N	151.3 E	284	N. W. Kurile Islands	3.7	4.7
18.6 S	69.9 W	116	N. Chile	4.6	5.0
6.9 N	126.1 E	58	Mindano	5.0	5.3
27.2 S	177.2 W	90	Kermadec	4.2	5.9
33.8 N	141.7 E	57	E. Coast Honshu	4.4	5.2
36.2 N	70.7 E	155	Hindu Kush	3.6	5.7
36.7 N	26.8 E	161	Turkey	3.1	5.4
45.8 N	26.6 E	134	Rumania	2.6	4.6
Undetermined Depth Events					
45.0 N	147.0 E	---	Kurile Islands	4.0	4.7
53.0 N	160.0 E	---	East Coast Honshu	4.4	4.8
11.2 N	139.1 E	---	Kirghiz	3.4	4.1
42.1 N	21.9 E	---	Yugoslavia	2.6	4.4
42.1 N	21.8 E	---	Yugoslavia	2.8	4.1
41.6 N	24.8 E	---	Bulgaria	3.4	4.2

APPENDIX III

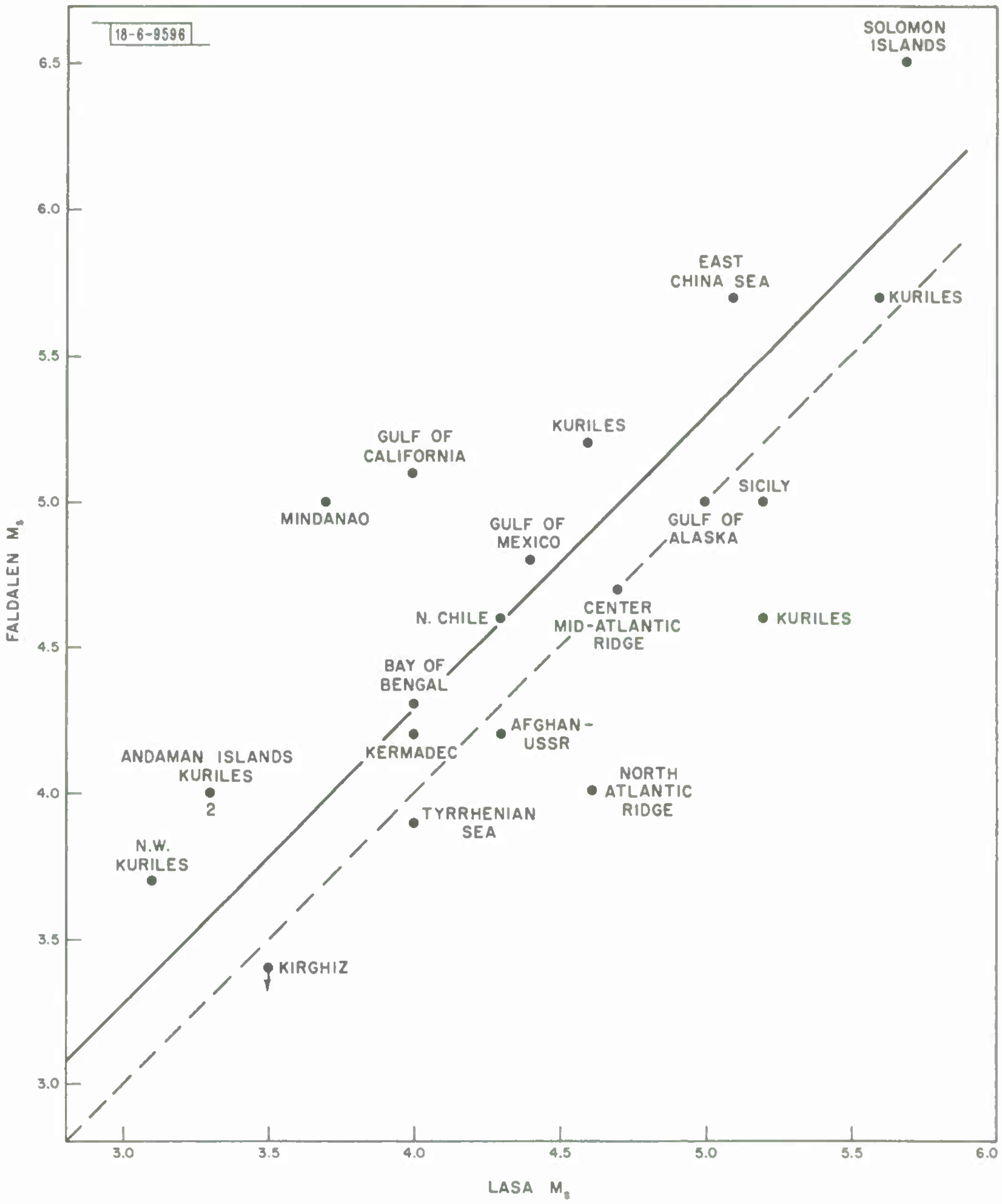


Fig. 1. Faldalen M_S vs LASA M_S for 21 worldwide earthquakes.

-6-9597

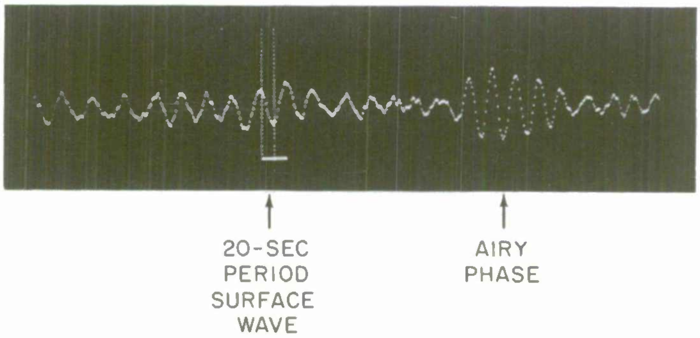
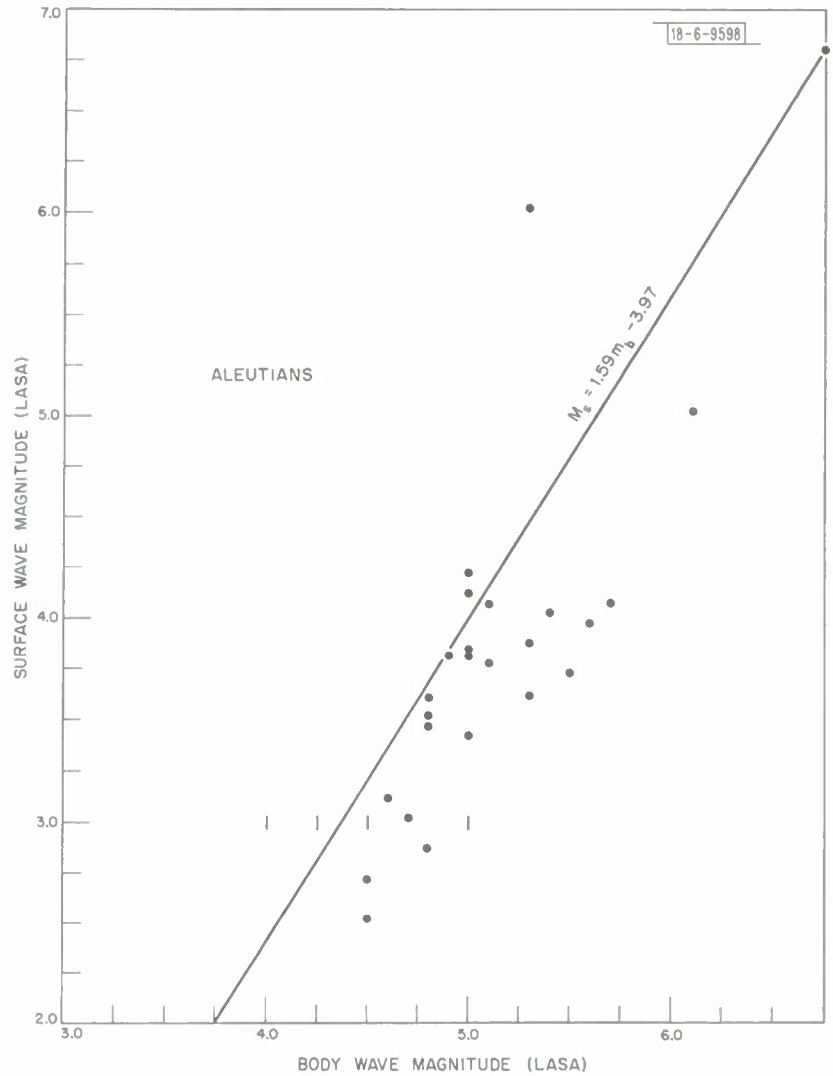
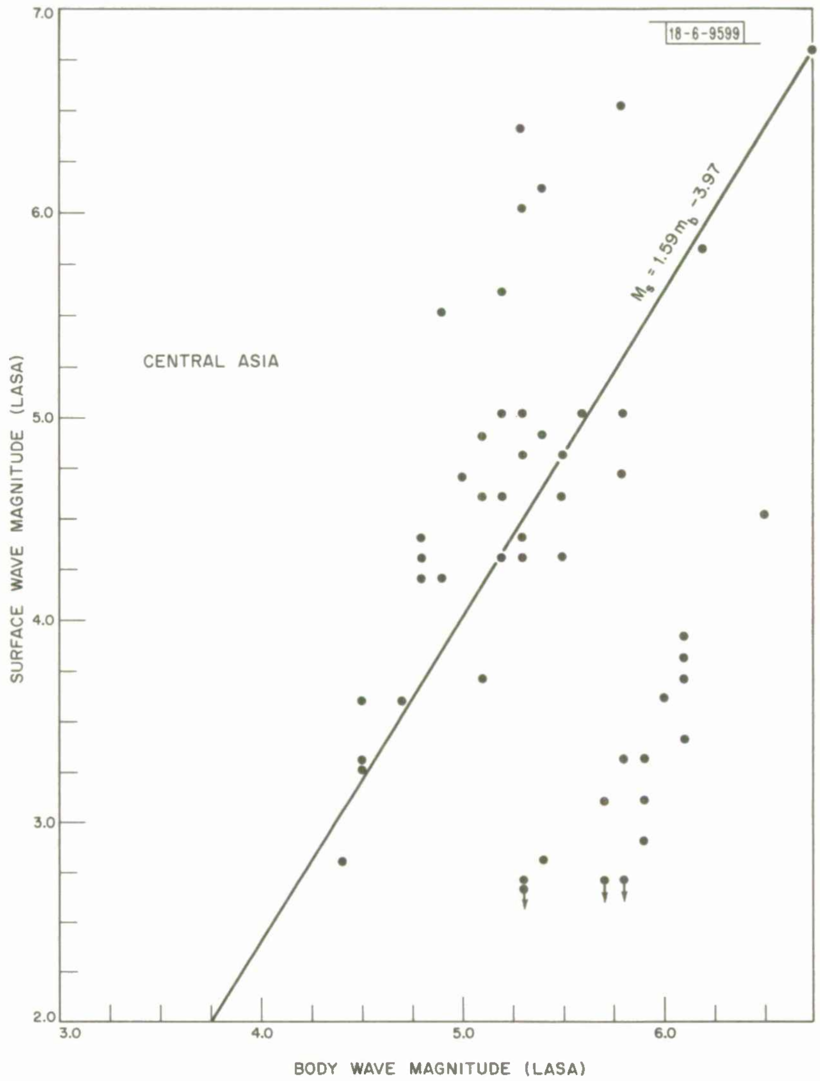


Fig. 2. An Airy phase arriving after the 20-second period Rayleigh wave marked by the cursor.



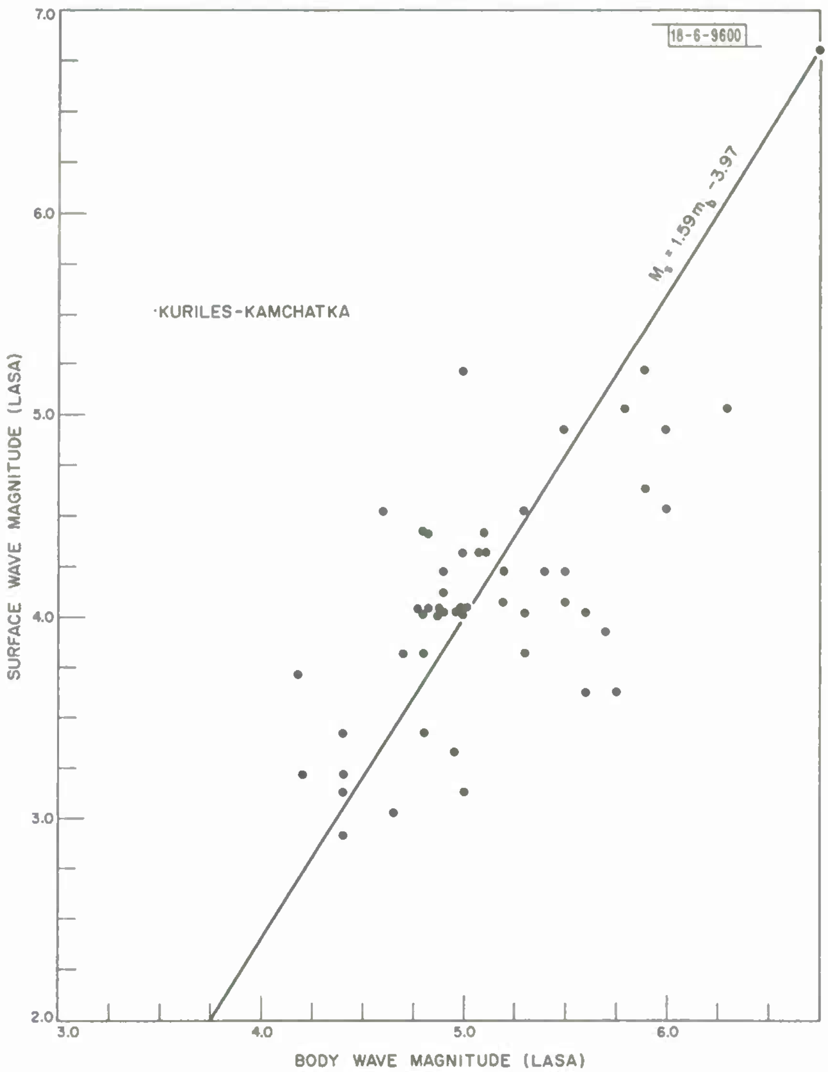
(a)

Fig. 3. M_S vs m_b plot of events recorded at LASA from four regions of the world (a. Aleutians, b. Central Asia, c. Kuriles-Kamchatka, d. Solomons-N. Caledonia-N. Hebrides).



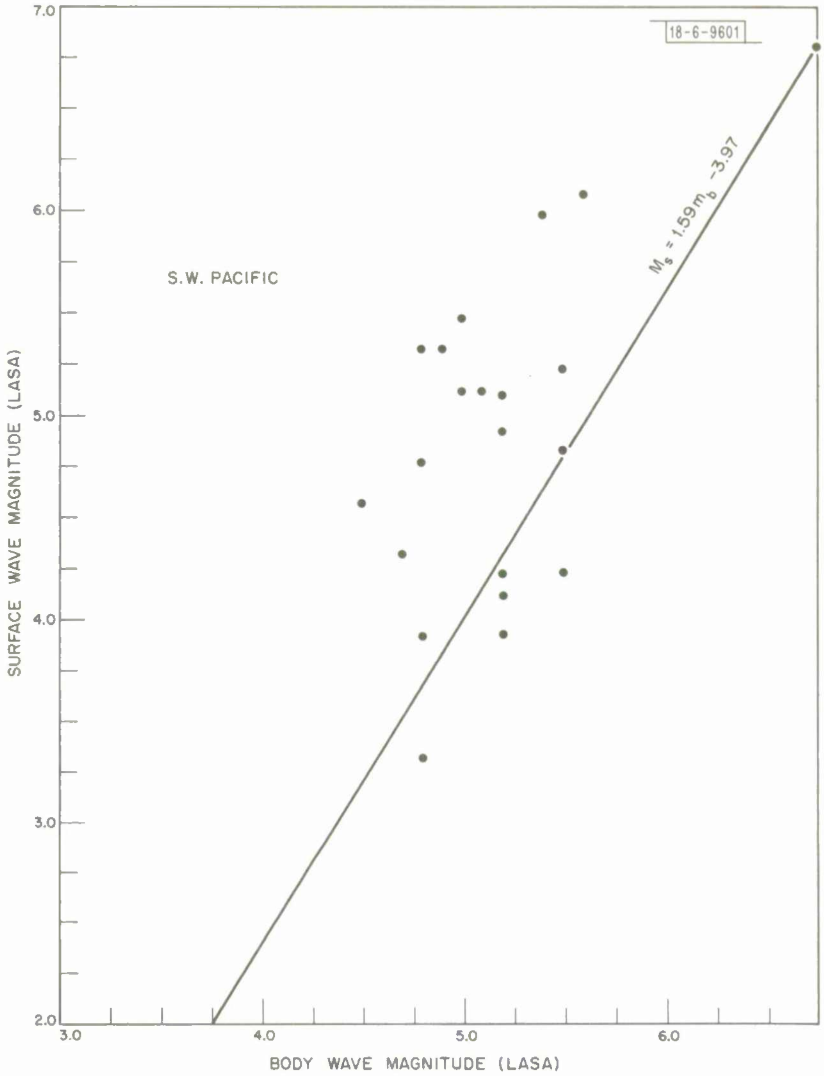
(b)

Fig. 3. Continued.



(c)

Fig. 3. Continued.



(d)

Fig. 3. Continued.

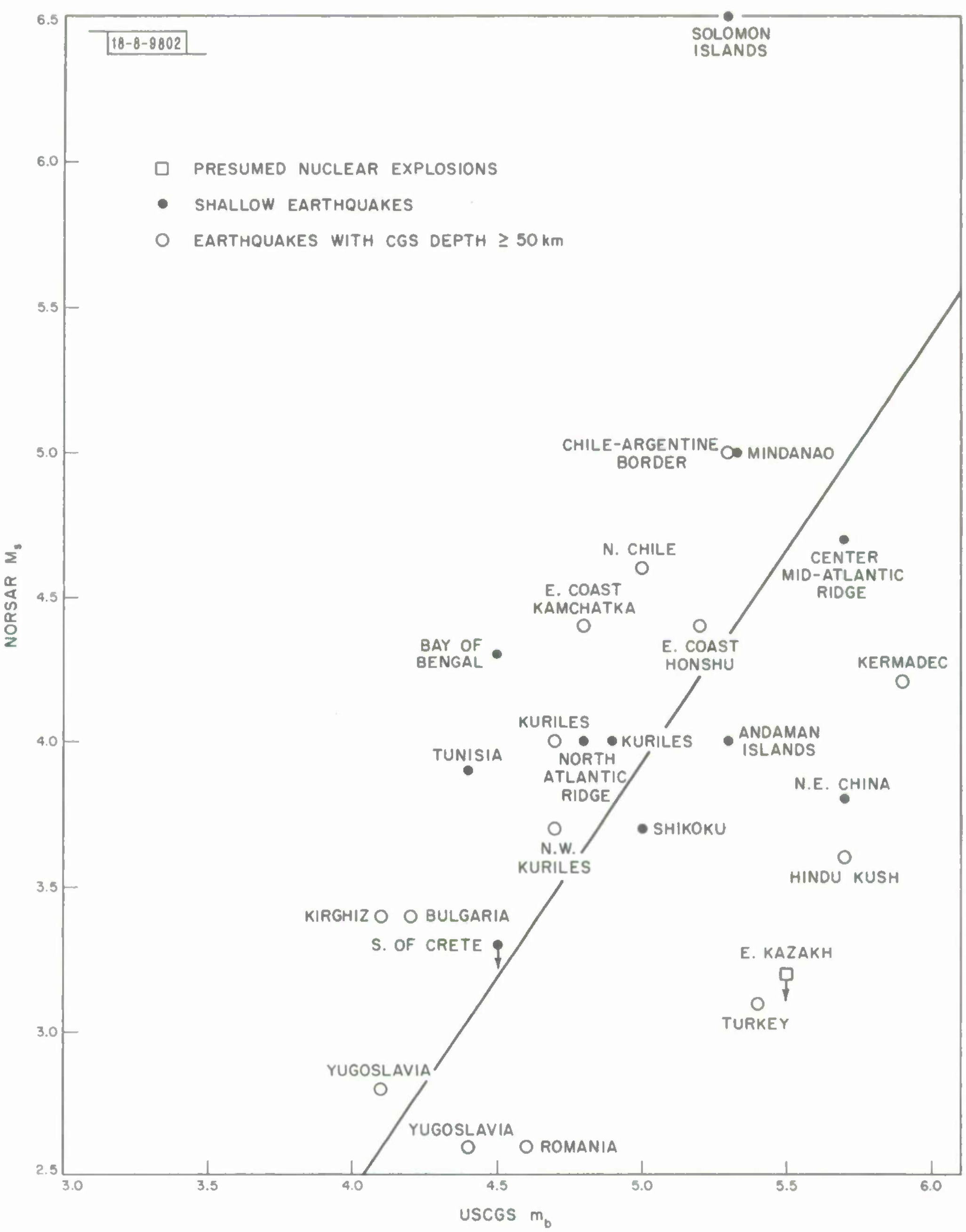


Fig. 4. M_S vs m_b plot of 25 earthquakes and one presumed explosion recorded at NORSAR.

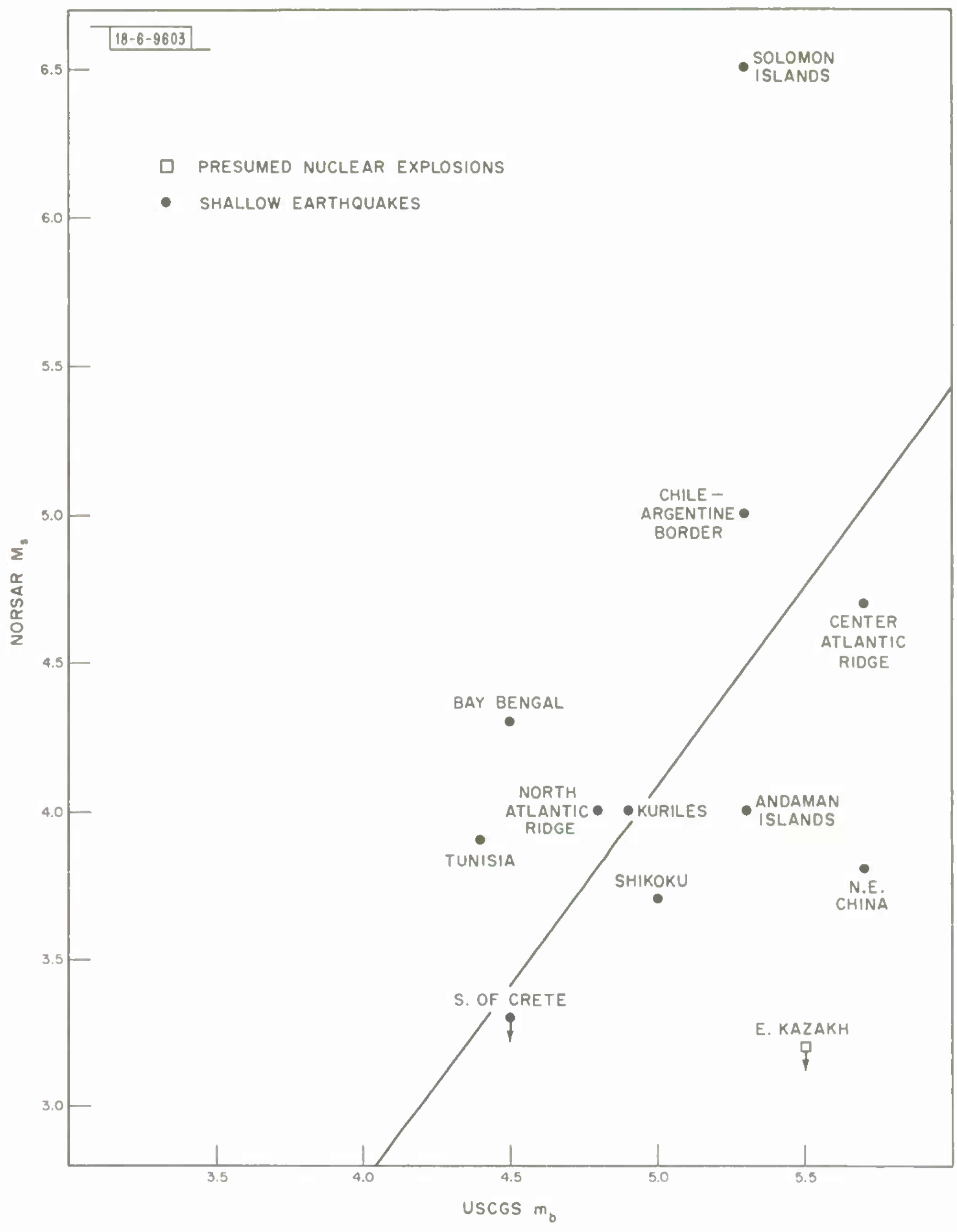


Fig. 5. M_S vs m_b plot of the events of Fig. 4 whose M_S was greater than 3.0 and depth (as determined by USCGS) was less than 50 km.

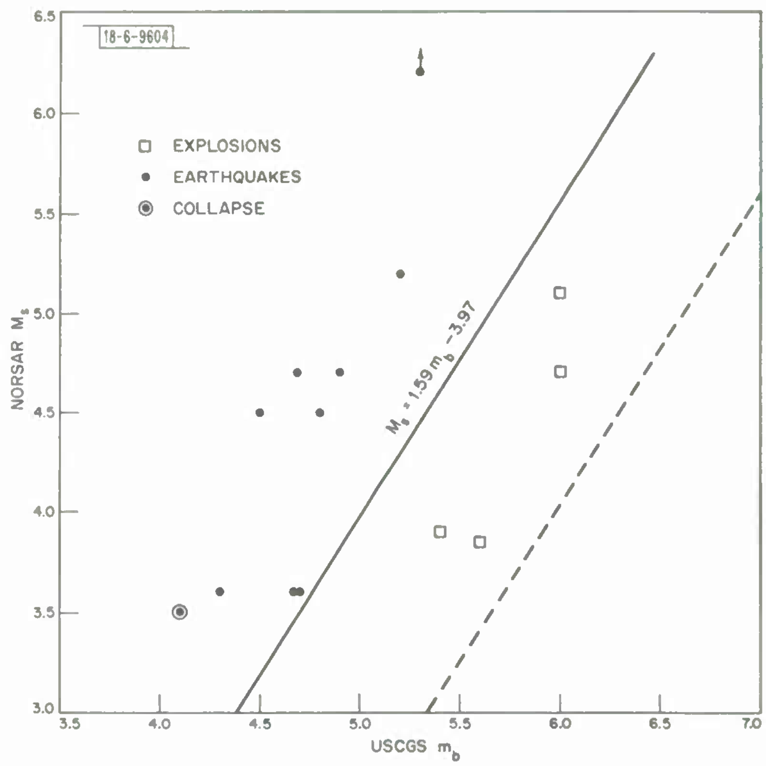


Fig. 6. M_S vs m_b plot of nine western U. S. and Mexican earthquakes, one NTS collapse and four NTS explosions.

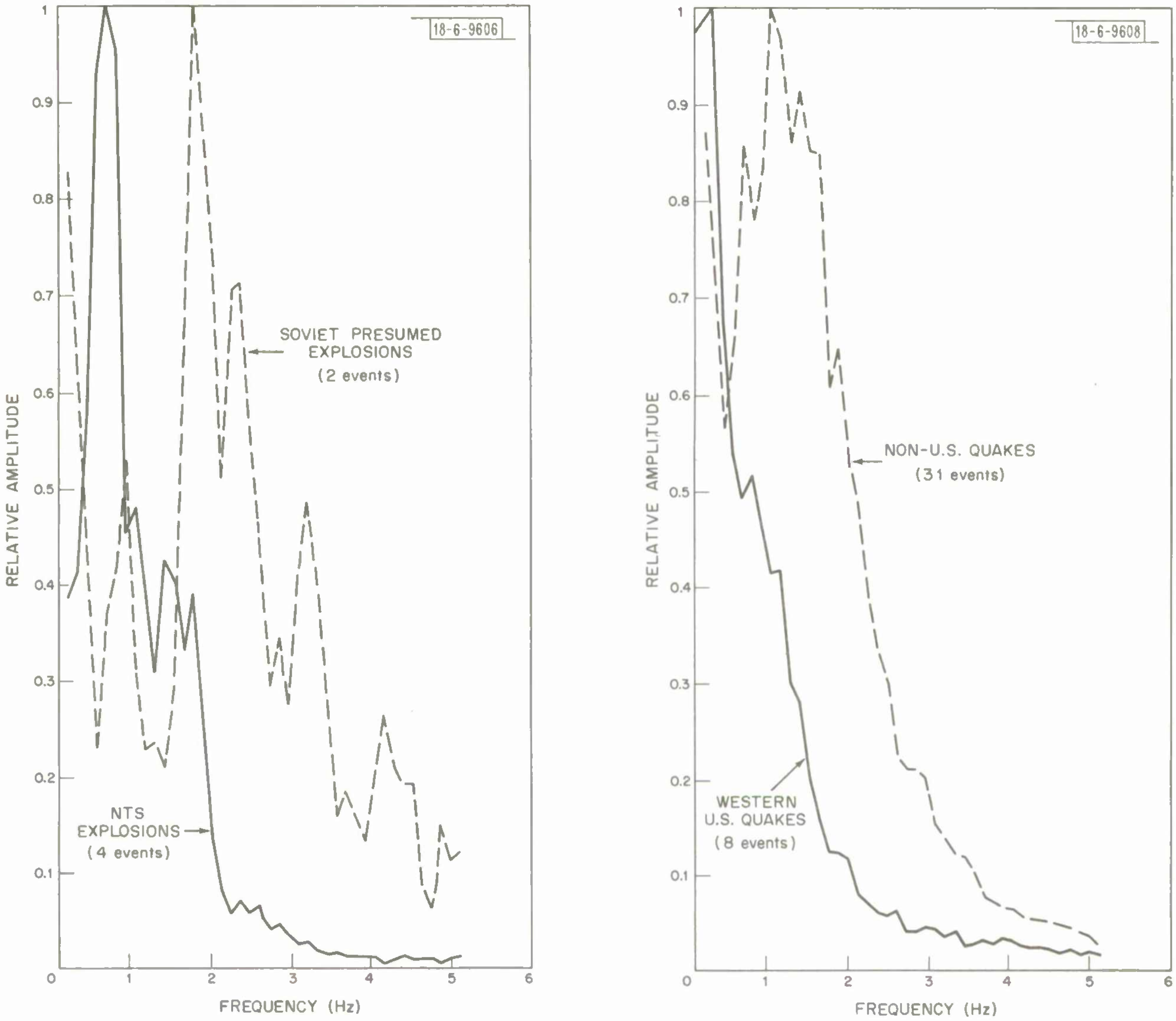


Fig. 7. Average P wave spectra recorded at NORSAR from U. S. and non-U. S. explosions and earthquakes. The spectrum from each event has been normalized by the square root of the sum of the squares of the spectral components. Each population was then averaged and normalized by the maximum spectral component for comparison.

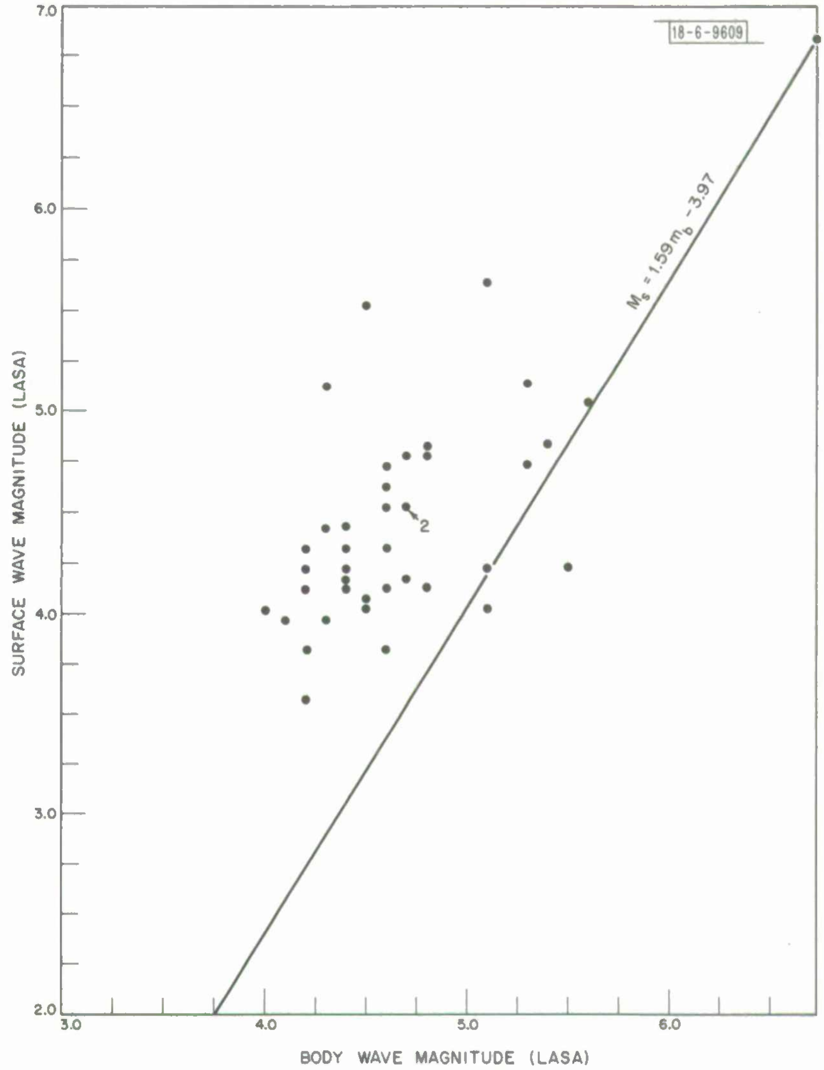


Fig. 8. M_s vs m_b plot of 39 Mid-Atlantic Ridge events recorded at LASA.

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13. ABSTRACT

Data from the short-period vertical subarray near Oyer and the multicomponent long-period seismograph near Faldalen, Oyer and Trysil, Norway, were used to investigate the discrimination of earthquakes and underground nuclear detonations using long-period to short-period energy ratio (M_s vs m_b).

14. KEY WORDS

Norway	seismic arrays
LASA	NORSAR
subarrays	